

# Sleep, Circadian Rhythms, and Performance During Space Shuttle Missions

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## ABSTRACT

Sleep and circadian rhythms may be disturbed during spaceflight, and these disturbances can affect crewmembers' performance during waking hours. The mechanisms underlying sleep and circadian rhythm disturbances in space are not well understood, and effective countermeasures are not yet available. We investigated sleep, circadian rhythms, cognitive performance, and light-dark cycles in five astronauts prior to, during, and after the 16-day STS-90 mission and the 10-day STS-95 mission. The efficacy of low-dose, alternative-night, oral melatonin administration as a countermeasure for sleep disturbances was evaluated. During these missions, scheduled rest-activity cycles were 20–35 minutes shorter than 24 hours. Light levels on the middeck and in the Spacelab were very low; whereas on the flight deck (which has several windows), they were highly variable. Circadian rhythm abnormalities were observed. During the second half of the missions, the rhythm of urinary cortisol appeared to be delayed relative to the sleep-wake schedule. Performance during wakefulness was impaired. Astronauts slept only about 6.5 hours per day, and subjective sleep quality was lower in space. No beneficial effects of melatonin (0.3 mg administered prior to sleep episodes on alternate nights) were observed. A surprising finding was a marked increase in rapid eye movement (REM) sleep upon return to Earth. We conclude that these Space Shuttle missions were associated with circadian rhythm disturbances, sleep loss, decrements in neurobehavioral performance, and alterations in REM sleep homeostasis. Shorter than 24-hour rest-activity schedules and exposure to light-dark cycles inadequate for optimal circadian synchronization may have contributed to these disturbances.

## INTRODUCTION

Travel is often associated with disturbed sleep, and spaceflight is no exception. In fact, spaceflight combines elements of jetlag and shift work—both of which are associated with disturbed sleep. In space, crewmembers may experience high workloads, anxiety, excitement, space motion sickness symptoms, and a noisy and often uncomfortably cold or warm sleeping environment. Even now, more than 40 years after the first human spaceflight, space travel is still an adventure, and not without risk, anxiety, and stress. The Space Shuttle, although much more comfortable than early Apollo cabins, is certainly not comparable to a hotel room. The pilot and commander often sleep in their chairs on the flight deck. Fortunate astronauts may have their own private sleep “cabinet.” More commonly, they must prepare for sleep by attaching to the wall of the middeck or Spacelab with Velcro. Astronauts are often scheduled to rise earlier every day, advancing their bed and wake times by five hours or more during the course of a mission; this is similar to the time zone change imposed by an eastbound trip from the United States to Europe. At the same time, either a sunrise or a sunset occurs every 45 minutes while the Space Shuttle is in low Earth orbit, sending potentially disruptive signals to the circadian pacemaker in those exposed to these 90-minute “days.”

### Biological Rhythms and Sleep Regulation

Earth is a highly periodic planet, and its environments are characterized by tidal, daily, monthly (lunar), and annual cycles. Natural selection has favored organisms equipped with internal biological clocks, particularly daily (circadian) clocks. Such innate clocks allow these living systems to anticipate the periodic environmental changes produced as Earth rotates around its axis. In mammals, circadian oscillations in nearly every aspect of physiology and behavior are driven by a pacemaker, the biological master clock that is located in the suprachiasmatic nuclei (SCN) of the anterior hypothalamus in the brain. The SCN drives circadian rhythmicity via both nerves and hormones. Circadian oscillations are generated by feedback loops of clock genes and their gene products. Indeed, Earth's rotations around its axis are engraved in the genome of nearly all living systems, including humans. Even when humans leave Earth, the circadian system travels along.

In the absence of a periodic environment, the human circadian clock oscillates at its intrinsic period—on average 24 hours and 11 minutes (Czeisler, 1999) in sighted people. When living on Earth, these circadian oscillations are synchronized to the 24-hour day (and resynchronised after humans travel through time zones) by the light-dark cycle. During low Earth orbit, the 24-hour natural light-dark cycle is absent and is replaced by a 90-minute external light-dark cycle related to the orbit of the Space Shuttle around the Earth. This interacts with the near-24-hour light-dark cycle associated with the activity-rest schedules produced by electric lamps and window shades aboard the spacecraft. This complex light-dark cycle may be inadequate to synchronize (or entrain) the human circadian clock to the scheduled rest activity, which often has an average period that is somewhat shorter than 24 hours.

In humans, the circadian pacemaker plays a pivotal role in sleep-wake regulation, and it is important to sleep and wake up at the appropriate phase of the circadian cycle (Dijk, 1995). The circadian clock enables people to stay awake and perform well for a full 16-hour waking day and then sleep well at night. The clock does this by providing a wake-promoting signal that becomes progressively stronger throughout the normal waking day. This signal suddenly dissipates at around 22–23:00, and is replaced by a sleep-promoting signal. Ground-based studies, in which sleep and wakefulness were scheduled to occur at all phases of the internal circadian cycle, have demonstrated that this circadian rhythm of sleep propensity is closely associated with the rhythm of plasma melatonin. This rhythm, which reflects variation in the synthesis of melatonin by the pineal gland, is driven by the SCN. The nocturnal rise of melatonin may help people fall asleep at night by quieting the output of the SCN, thereby silencing the wake-promoting signal. When individuals attempt to sleep outside this phase of melatonin secretion, sleep is disrupted. Ground-based research has shown that administration of melatonin when sleep is attempted at circadian phases at which the body's own melatonin is absent increases sleepiness, improves sleep consolidation, and may facilitate the synchronization of the circadian clock to the desired rest-activity cycle.

### Circadian Rhythms and Spaceflight

Over the years, NASA has developed regulations designed to reduce the magnitude of daily shifts in scheduled sleep and to protect scheduled crew rest time. (Although a procedure called “slam shifting,” which involves abrupt shifts of up to 12 hours, is now used to align the sleep-wake schedules of Space Shuttle and International Space Station crews upon docking.) Moreover, astronauts are often highly motivated to complete necessary repairs or payload activities after hours. They may be called upon to deal with “off-nominal” situations at all times of day or night, and may stay up later than the scheduled bedtime. Nonetheless, in most cases, they will be awakened at the scheduled wake time regardless of how late they retired.

Data on medication use in space supports the conclusion that sleep is disturbed during Space Shuttle missions. NASA analysis of 219 records of the use of medication during low Earth orbit Space Shuttle missions found that sleeping pills are the most commonly used medication. Sleep medications were reportedly used by astronauts throughout many missions, in contrast to the motion-sickness remedies that are used primarily during the first few days of such missions. The frequent use of sleeping pills is all the more remarkable given that astronauts carry a high homeostatic sleep pressure (i.e., have a strong need to sleep) during the mission, since they sleep on average only six to 6.5 hours per day in space (Monk, 1998; Santy, 1988).

On Earth, sleep disturbance and chronic sleep restriction lead to decrements in daytime performance that jeopardize productivity and safety in the workplace. There is no reason to believe that this would be different in space. Hypnotics that bind to the GABA<sub>A</sub>-benzodiazepine receptor complex (the most commonly prescribed sleeping pills) have been shown to impair

daytime performance and the ability to respond quickly and adequately when awakened from hypnotic-induced sleep.

It remains unknown whether there are aspects specific to space travel and the space environment that disrupt sleep. Is the timing of sleep disrupted because astronauts' biological clocks are no longer exposed to the Earth's 24-hour day-night cycle? Is the sleep stage composition of sleep need altered in space because floating in microgravity is less fatiguing than walking upright on Earth?

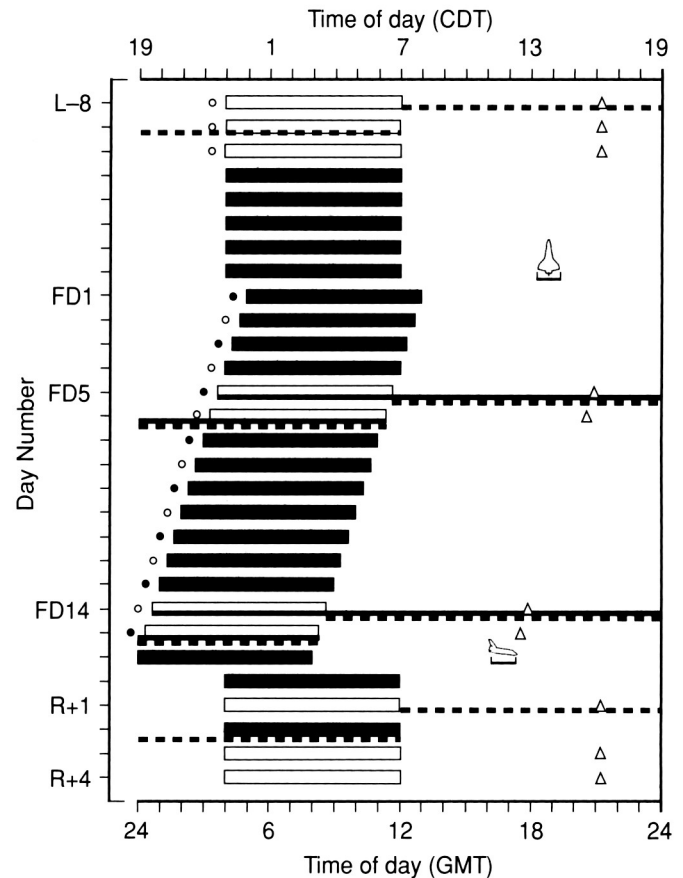
To answer these questions, we investigated sleep, performance, and circadian rhythms in five astronauts (STS-90: four; STS-95: one) and studied the light-dark cycles to which crewmembers were exposed during these two Space Shuttle missions. The efficacy of melatonin as a countermeasure for sleep disturbances during spaceflight was investigated as well. To assess the impact of spaceflight, extensive baseline measurements were obtained prior to the flights. Astronauts agreed to refrain from the use of hypnotics so that the effects of spaceflight on unmedicated sleep could be evaluated. Effects of re-adaptation to the Earth environment were evaluated by recording sleep, performance, and circadian rhythms immediately after return. The results of our sleep experiment and the experiment of our team members on respiration during sleep in space have been reported in full elsewhere (Dijk, 2001; Elliott, 2001). Here we present a brief overview of the background to this research, summarize the main results, and compare our results to those of other researchers who have investigated sleep in space and on the ground.

## METHODS

### Work-Rest, Rest-Activity Schedules during STS-90 and STS-95

The work-rest schedules of astronauts are tailored to the scheduled time of launch and reentry. The crew of both STS-90 and STS-95 were stationed at the Johnson Space Center (JSC) in Texas and lived on the local time zone (Central Daylight Time (CDT)). Three to four days prior to scheduled launch they left for the Kennedy Space Center (KSC) in Florida, travelling eastward through one time zone (Eastern Time zone).

The launch windows for STS-90 and STS-95 were both located conveniently in the afternoon. In fact, the launch schedules of STS-90 and STS-95 were specifically designed to avoid the necessity of prelaunch circadian phase shifting. To achieve this, launch occurred at 14:19 Eastern Daylight Time for STS-90 and 14:20 Eastern Standard Time for STS-95. Crewmembers woke about seven hours before launch, and the first eight-hour sleep episode in space was scheduled to begin at 01:00 hours. Figure 1 is a raster plot of the mission schedule; it illustrates that the sleep-wake schedules in space were not identical to a normal 24-hour cycle. Astronauts were to rise and retire earlier every day by about 20 (STS-90) and 35 minutes (STS-95). This was done to assure that on the day of reentry, sleep-wake schedules were timed appropriately. Bed and wake times advanced by as much as five hours in the course of these missions.



**Figure 1.** Experimental schedule and scheduled time of the rest-activity cycles for the Neurolab mission (STS-90). This raster plot illustrates when measurements were made shortly prior to (L-), during (FD), and after (R) the mission. Additional baseline measurements were made two months and one month prior to flight. In this figure, flight days (FDs) are numbered such that FD1 starts at launch and ends at the end of the first inflight sleep episode. Timing of scheduled polysomnographic recordings is indicated by open horizontal bars; neurobehavioral performance tests by triangles; urine collection sessions by dashed horizontal lines; and body temperature recordings by a solid horizontal line. Placebo (open circles) and melatonin (closed circles) administration prior to scheduled sleep episodes is indicated for one treatment group (see Dijk et al. (Dijk, 2001) for a description of differences between treatment groups). Time of day is indicated as Central Daylight Time (CDT: upper horizontal axis) and Greenwich Mean Time (GMT: lower horizontal axis). (From Dijk, 2001, with permission; reproduced from *The American Journal of Physiology*.)

### Measuring Sleep and Wakefulness

To determine how well the astronauts could adhere to the rest-activity schedules, we used actigraphy—a continuous recording of activity of the nondominant wrist (Figure 2). Ground-based and flight-based studies have shown that such actigraphic recordings can be analyzed to obtain a reliable estimate of total sleep time and other sleep parameters. Figure 3 illustrates the rest-activity cycle in one crewmember of STS-90.



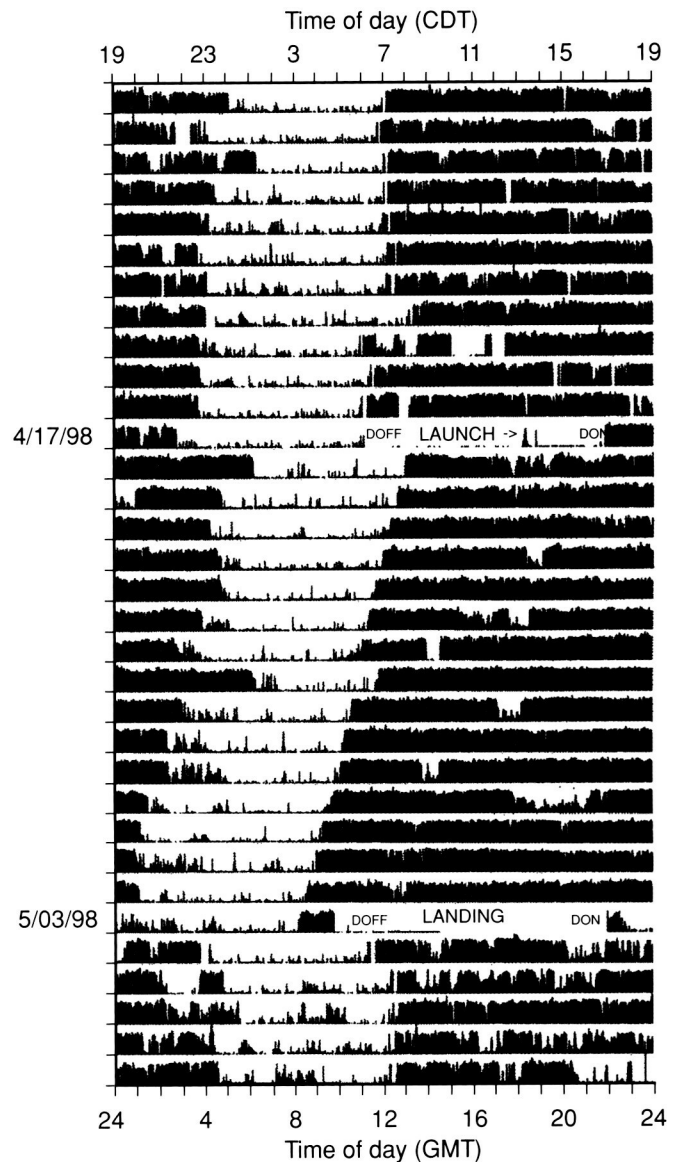
**Figure 2.** Long-term recording of rest-activity cycles can be accomplished by actigraphy. In this photograph taken during the STS-95 mission, Chiaki Mukai is wearing an actigraph on her nondominant wrist.

### Polysomnographic Recording of Sleep

To investigate how sleep structure (i.e., the different stages of sleep from light to deep) was affected, we recorded brainwaves (electroencephalogram (EEG)), submental muscle tone (electromyogram (EMG)), and eye movements (electro-oculogram (EOG)) during sleep episodes in the first half and second half of the missions (Figure 1). This kind of recording is called polysomnography. These data were compared to similar recordings obtained during three sessions prior to (two months, one month, and one week beforehand) and immediately after the mission. The recordings were made using a digital sleep recorder and a specially designed sleep net (Figure 4). (See also technical report by Dijk et al. in this publication.) Human sleep consists of non-rapid eye movement (nREM) sleep and REM sleep. nREM sleep can be further subdivided into stage 1, 2, 3, and 4 sleep. Stages 3 and 4 (also called slow wave sleep (SWS)) are often considered the deepest stages of sleep and are thought to be important for the recovery aspects of sleep (Figure 5). During normal nocturnal sleep on Earth, SWS declines in the course of a sleep episode and REM sleep increases. During a normal night, there will be some wakefulness as well. It takes time to fall asleep and at the end of the night, individuals may wake up several times before finally getting out of bed.

### Light-Dark Cycles and Circadian Rhythms

Extensive research on the effects of light exposure on human circadian rhythms has established that the light-dark cycle is a powerful synchronizer of the human circadian pacemaker. Scheduled light exposure can be used to shift the rhythms of astronauts prior to those missions in which the launch window dictates rest-activity cycles to be timed out of synchrony with the normal rest-activity cycle on Earth (Czeisler, 1991). Light levels lower than ordinary room light can modulate the timing of circadian rhythms, and can also exert direct effects on alertness (along with its EEG and EOG correlates) and neuroendocrine variables such as melatonin synthesis. Although the human



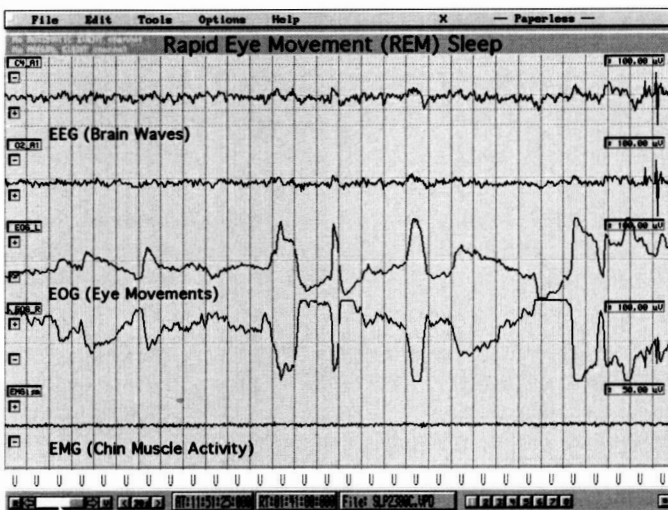
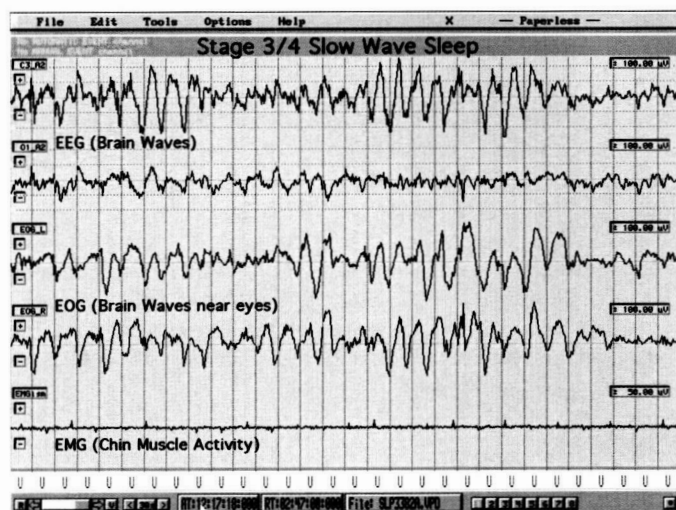
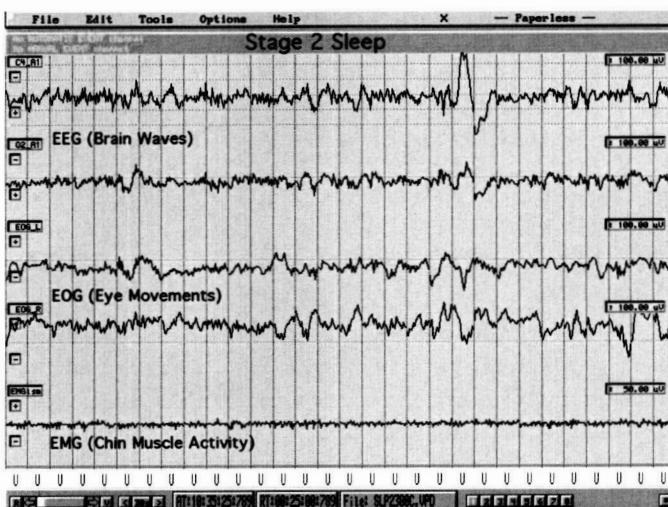
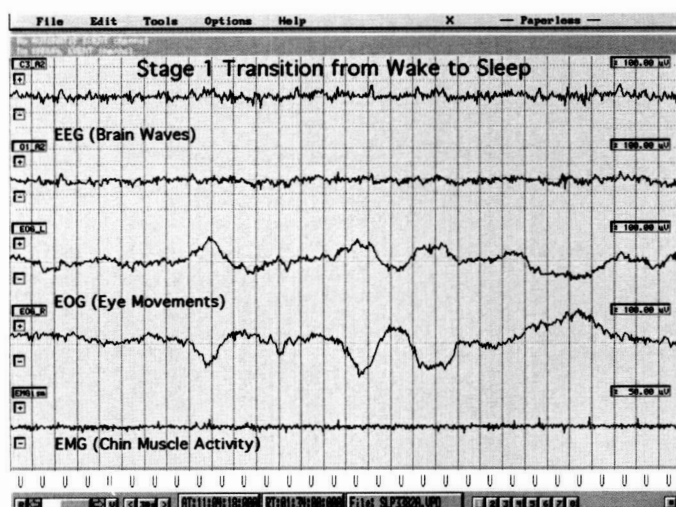
**Figure 3.** Recording of the rest-activity cycle of an astronaut prior (before 4/17/98), during (4/17/98-5/03/98), and after the Neurolab mission by actigraphy. Consecutive 24-hour segments are plotted below each other. No actigraph was worn at the time of launch or landing. Note the regular advance of activity onset and the variability in the offset of activity during spaceflight, and the acute delay in the rest-activity cycle upon return to Earth. (From Dijk, 2001, with permission; reproduced from *The American Journal of Physiology*.)

circadian pacemaker is most sensitive to light during the biological night—i.e., when melatonin is present in plasma—light exposure during the biological day also exerts effects on circadian phase. This implies that complex light-dark cycles and unscheduled light exposure during spaceflight may have both beneficial and detrimental effects on the synchronization of the human circadian pacemaker. To assess this, light levels were recorded throughout the mission in the flight deck, middeck, and Spacelab using Actillum light recorders (Ambulatory Monitoring, Inc., Ardsley, NY).





**Figure 4.** Brainwaves, eye movements, and airflow were recorded by means of a sleep net and additional sensors. This photograph shows payload commander Rick Linnehan being instrumented by payload specialist Jay Buckey during the STS-90 mission.



**Figure 5.** Brainwaves, eye movements, and submental muscle tone during stages of sleep. These traces were recorded during the Neurolab mission and downlinked to JSC immediately after the recording. This allowed researchers on the ground to inspect the quality of sleep recordings during the mission.

To determine whether the crewmember's internal circadian rhythms during these missions maintained adequate synchronization with the rest-activity schedules, we measured core body temperature and urinary cortisol rhythms on two occasions during the STS-90 mission (Figure 1) as well as prior to and after the mission. Both body temperature and urinary cortisol have strong circadian rhythms and can be used to follow the changes in circadian rhythms.

## Performance and Mood

One important question was whether changes in sleep duration and circadian rhythms would be related to a deterioration of performance during wakefulness. This question is difficult to answer directly because no data exist on performance during spaceflights during which there were no sleep and circadian rhythm disturbances. We could, however, compare performance during spaceflight with performance prior to and after spaceflight. On STS-90 and STS-95, we assessed performance and mood on a specific test battery designed in collaboration

with Dr. David F. Dinges of the University of Pennsylvania. This test battery included tests of memory, calculation ability, vigilance, and coordination. In addition, it had several subjective scales to rate sleepiness and mood.

## Melatonin

One other objective of our studies was the evaluation of the efficacy of melatonin as a countermeasure for the disturbances of sleep and circadian rhythms during spaceflight. Melatonin is thought to be devoid of some of the side effects of standard hypnotics and could be an alternative to typical sleeping pills. We sought to assess objectively the efficacy of melatonin in space. In preparation for the Neurolab mission, we first evaluated the efficacy of two doses of melatonin (0.3 and five mg) in a ground-based study. In this experiment, the efficacy of melatonin was investigated at all circadian phases by scheduling subjects to a 20-hour sleep-wake routine. During the scheduled wake episodes, light levels were low (<five lux). Our initial analyses of these data indicated that 0.3 mg was as effective as five mg in inducing sleep when sleep occurred outside the phase of endogenous melatonin secretion. With the 0.3-mg dose, elevation of plasma melatonin concentration returned to baseline after the sleep episode. We therefore selected the 0.3-mg dose for evaluation in space in a double-blind, placebo-controlled experiment in which placebo and melatonin nights alternated.

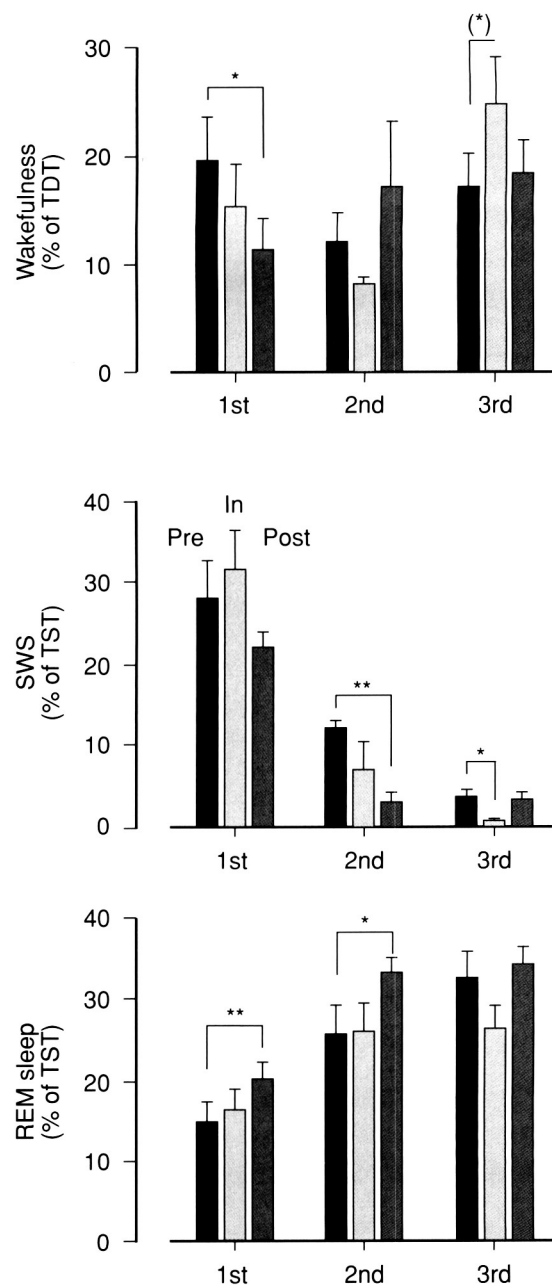
## RESULTS

### Actigraphy

Figure 3 shows the 24-hour rest-activity cycle prior to flight (and the approximately one-hour phase-advance associated with the travel from JSC to KSC) in one astronaut. Inflight, the progressive phase-advance of wake time associated with the shorter-than-24-hour sleep-wake schedule is clearly visible. Note the major deviation from this schedule on FD8 due to operational demands. It is also interesting to note that the day-to-day variability in the onset of activity (wake time) was much smaller than the day-to-day variability in offset of activity (bedtime). After landing, we can see the abrupt approximately four-hour phase delay of the rest-activity cycle, comparable to flying westward through four time zones. Actigraphic recordings in the other astronauts gave very similar patterns. Quantitative analysis showed that according to these actigraphic recordings, astronauts' average daily sleep period time (i.e., the time from sleep onset to final awakening) was on average only 427.6 (SE: 6.8) minutes; this was approximately 30 to 40 minutes less per night than during sleep episodes prior to and after flight. During these seven hours, a half-hour was spent awake such that total sleep time was approximately 6.5 hours. On some nights, total sleep time was reduced to as short as 3.8 hours.

### Polysomnographic Recordings

Figure 6 illustrates the time course of wakefulness, SWS, and REM sleep during sleep episodes recorded in space, prior to spaceflight, and after return to Earth. SWS declines from the first



**Figure 6.** Wakefulness (upper panel), SWS (middle panel), and REM sleep (lower panel), in the first, second, and final third of sleep episodes during the preflight (first solid bar), inflight (second grey bar), and postflight (third solid bar) segments. Wakefulness is expressed as percentage of total dark time (TDT). SWS and REM sleep are expressed as percentage of total sleep time (TST). N=5; Sleep episodes after intake of melatonin are not included. Significance of pair-wise comparisons are indicated: (\*)= $p<0.1$ ; \*= $p<0.05$ ; \*\*= $p<0.01$ . Figure based on data published in Dijk et al. (Dijk, 2001).

to the last third of the sleep episode under all three conditions. REM sleep increases from the beginning to the end of sleep. Thus, the overall structure and temporal organization of sleep were not markedly altered during and after spaceflight. It should be mentioned, though, that on average the astronauts rated their

sleep as of poorer quality than compared to sleep on Earth. Sleep efficiency (i.e., percentage of time spent asleep/time in bed) was just below 85% inflight, very similar to the preflight and postflight values. Detailed analysis revealed several intriguing alterations in sleep structure in space and upon return to Earth. In the first third of sleep, less wakefulness was present in space and after return than prior to the mission. Thus, astronauts were very well able to fall asleep despite their advanced sleep schedule (inflight) and delayed sleep time (postflight). Interestingly, there was a tendency for more wakefulness in the last third of sleep episodes during the inflight segment. This is surprising because during eastward travel (advance of sleep relative to the endogenous circadian rhythms), it is difficult to fall asleep and difficult to awaken on scheduled local time. SWS was reduced in the last third of inflight sleep episodes.

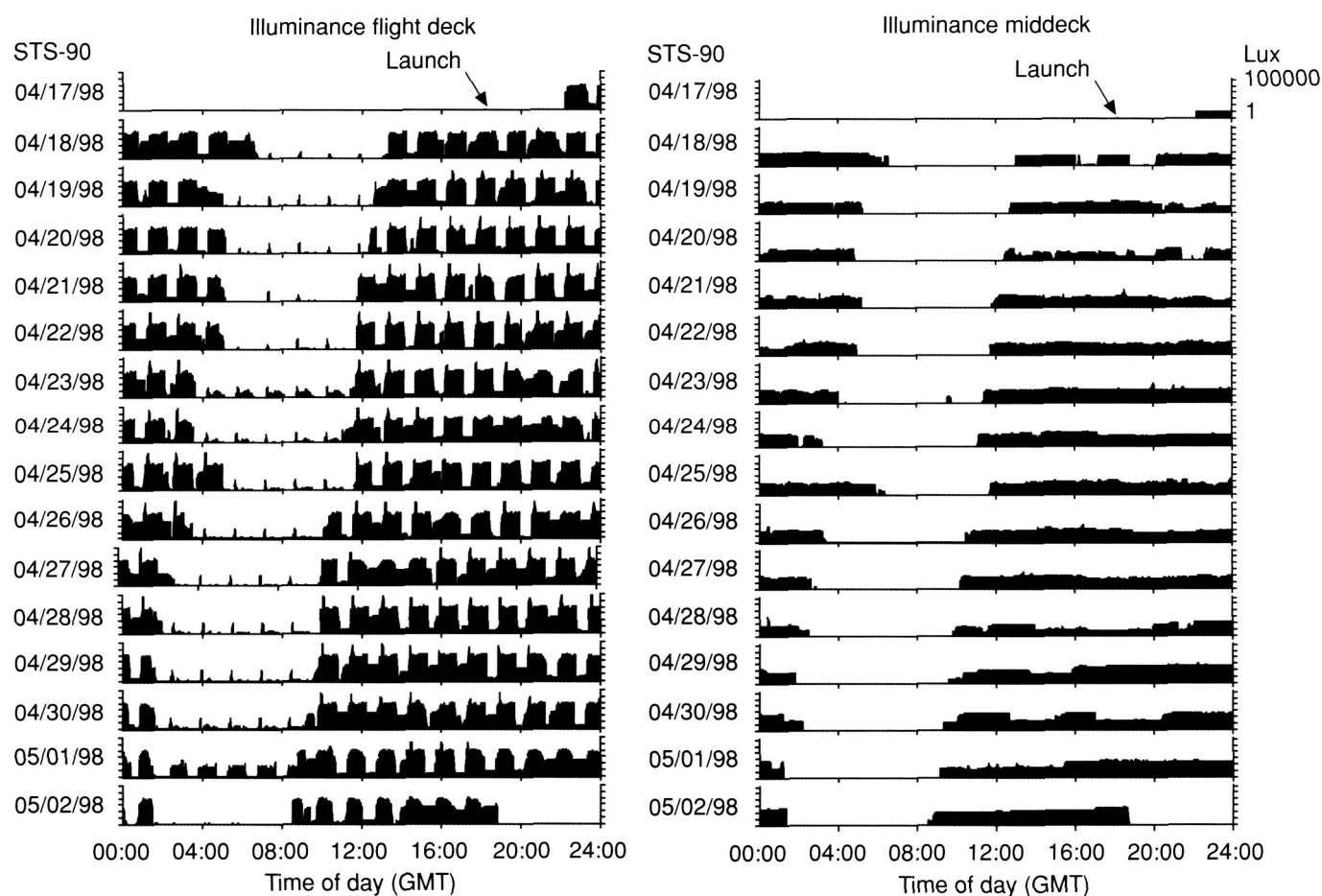
For REM sleep, the most marked changes occurred after return to Earth. There was more REM sleep in both the first and second third of sleep episodes recorded after landing. Furthermore the latency to REM sleep was significantly reduced from 86.4 ( $\pm 13.1$ ) minutes prior to flight to only 43.3 ( $\pm 2.5$ ) minutes postflight. During the second sleep episode after landing (no recording was obtained during the first sleep

episode), REM sleep expressed as a percentage of total sleep time was as high as 32%, compared to 24% preflight.

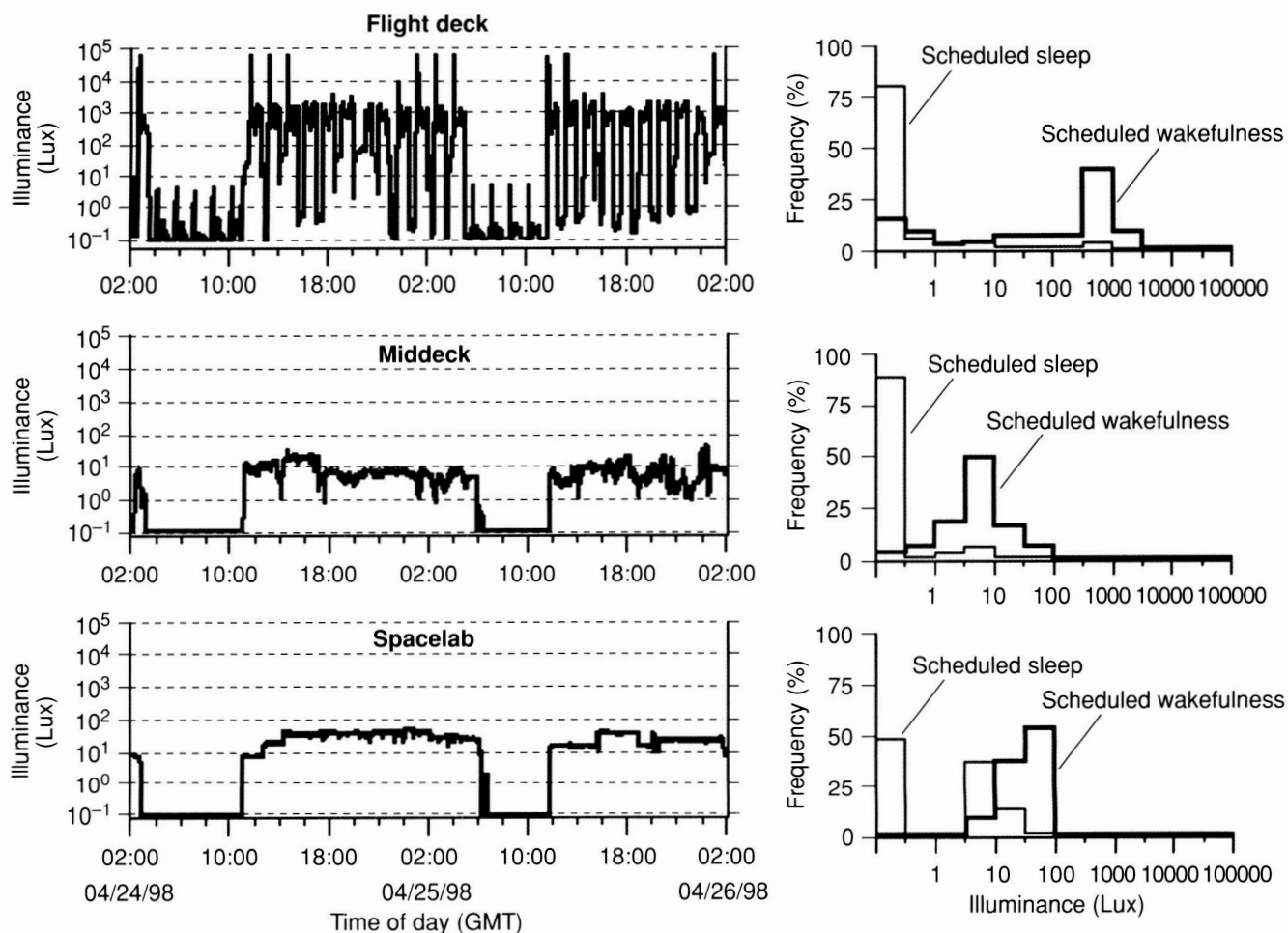
Comparison of the estimates of sleep derived from actigraphy and polysomnography revealed a surprising difference. It appeared that astronauts slept longer when fully instrumented for sleep monitoring. Total sleep time (as derived from actigraphy) during polysomnographically recorded sleep episodes was near seven hours compared to less than 6.5 hours for the nights during which no full polysomnographic recording was obtained.

### Light Levels

Light recordings on the flight deck throughout the STS-90 mission revealed very complex and highly variable light-dark cycles. An approximately 90-minute periodicity, associated with the orbit of the spacecraft around the Earth, is superimposed on a slightly shorter than 24-hour oscillation, associated with the scheduled rest-activity cycle (Figure 7). On the flight deck, light levels as high as 79,000 lux were observed. Although on the flight deck the shades were pulled down during scheduled sleep episodes, orbital dawn still entered the flight deck and



**Figure 7.** Illuminance on the flight deck and middeck during the Neurolab mission. Days are plotted below each other. Illuminance (lux) is plotted on a logarithmic scale. Please note the 90-minute recurrence of orbital dawn on the flight deck and the shorter-than-24-hour light-dark cycle on the middeck. Figure based on data from Dijk et al. (2001).



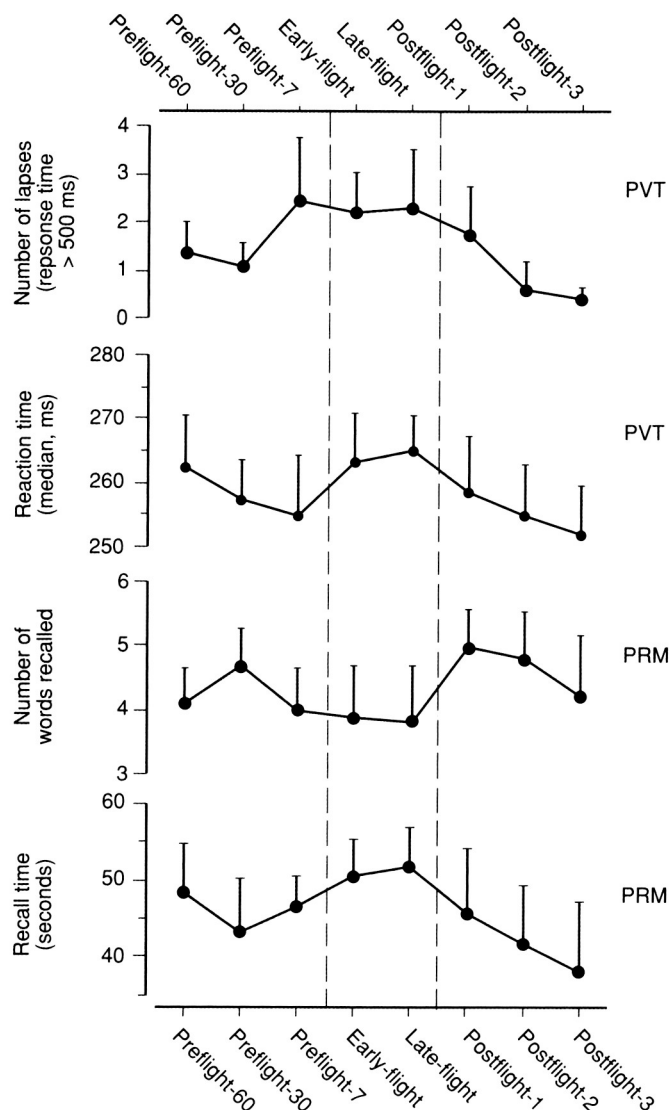
**Figure 8.** Time course of illuminance (48-hour segment) recorded on the flight deck, on the middeck, and in the Spacehab (left panels). Right panels: Relative frequency distribution of illuminances (bin width 0.5 log units) during scheduled wakefulness (heavy solid line) and scheduled sleep (thin solid line) for the flight deck (upper right panel), middeck (middle right panel), and Spacelab (lower, right panel). Frequency distributions were derived from all data collected during the STS-90 mission. (From Dijk, 2001, with permission; reproduced from *The American Journal of Physiology*.)

the average illuminance during scheduled sleep episodes was 73 lux (Figure 8). On the windowless middeck, the 90-minute periodicity was not present. Only the shorter-than-24-hour light-dark cycle associated with the rest-activity cycle characterized the light environment in this compartment. Light levels on the middeck were very low. The highest illuminance observed was 93 lux, and the mean value during scheduled wake episodes was only nine lux. To put these numbers in perspective: illuminance on the surface of a desk in a well-lit room may be 300 to 500 lux. During a bright sunny day, ambient outdoor light intensity may reach 100,000 lux. The temporal pattern of illuminance in the Spacelab (STS-90) and Spacehab (STS-95) was similar, with average levels also rather low, although slightly higher than on the middeck. However, the Spacelab had a window that provided additional illumination when unshaded. The illuminances we recorded were obtained from light recording devices mounted on the interior walls of the spacecraft and, therefore, do not accurately represent light exposure of individual astronauts who moved around from one compartment to the other.

### Circadian Rhythms (Body Temperature and Urinary Cortisol)

Several features of circadian rhythms in space emerged. Interestingly, the onset of the sleep episode was still associated with a drop in core body temperature, despite the absence of “postural” changes. In other words, “masking” of the endogenous circadian core body temperature rhythm by behavioral cycles is still present during spaceflight. Consequently, a simple recording of body temperature may not provide a reliable estimate of the phase of the circadian pacemaker, even in space. Nonetheless, the amplitude of the “masked” temperature rhythm was attenuated in space. Urinary cortisol secretion may be less affected by behavioral cycles and better reflect the status of the circadian pacemaker. We quantified the circadian rhythm of cortisol preflight, early in the flight, late in the flight, and postflight. Preflight and early inflight urinary cortisol reached a peak shortly after scheduled wake time and started to decline within two to four hours. In the second half of the mission, this decline did not occur until six hours after scheduled wake time.





**Figure 9.** Neurobehavioral performance measures derived from the psychomotor vigilance test (PVT) and the probed recall memory (PRM) test during three preflight segments, two inflight segments, and three postflight segments.  $n=5$  (except for post-flight 1 when  $n=4$ ). (From Dijk, 2001, with permission; reproduced from *The American Journal of Physiology*.)

### Performance Measures

In general, several measures of performance indicated better performance on Earth and deterioration in flight. Some of the data are summarized here (Figure 9). Thus, the lowest number of lapses (i.e., reaction times longer than 500 ms) were observed two months and one month prior to flight, and on the third and fourth day after landing. Median reaction times were longer inflight. On a probed recall memory task, time to recall was longest, and fewer words were recalled inflight. After flight, recovery of performance occurred. Similar patterns were observed on other tasks as well as for subjective assessments of mood.

Interestingly, for some of the performance measures, decrements were already observed during the L-7 segment;

i.e., shortly before launch. This may be related to prelaunch apprehension or the increased workload leading to sleep loss prior to launch.

### Melatonin Trial

Comparison of sleep after placebo and melatonin, however, did not reveal significant effects of melatonin on sleep in space. This may be related to the specific pattern of melatonin administration (alternating with placebo), the circadian phase of the administration of melatonin on this protocol, or changes in pharmacokinetics of melatonin during spaceflight.

## DISCUSSION

Our analyses of sleep in space confirm and extend previous observations (see Stampi, 1994; Gundel, 1997; Monk, 1998; Dijk, 2001; and references therein). They confirm that sleep in spaceflight is shorter than on Earth, and the actigraphic recordings indicate that this problem may be more serious than polysomnographic sleep recording sessions would suggest.

### Increase in REM sleep after flight

The effects on REM sleep after the mission are intriguing. Because REM sleep is under control of the circadian clock and sleep times were shifted throughout the mission and then suddenly shifted back upon return, circadian effects may in part explain this increase in REM sleep. However, our analyses of the circadian rhythms of core body temperature and urinary cortisol secretion do not support such an interpretation. Previously, (Frost, 1977) reported an increase in REM sleep after Skylab missions, and he also dismissed a circadian explanation for this phenomenon. An alternative explanation for this REM rebound is that it reflects a homeostatic response to the loss of REM sleep incurred during spaceflight. A more speculative explanation is that this massive increase in REM sleep represents a response to the re-adaptation to one-G. REM sleep has been implicated in learning processes related to sensory-motor tasks in particular. Could it be that "relearning" to walk on Earth is closely related to this REM sleep increase?

### Longer sleep times with sleep instrumentation in place

The data show that on nights when the astronauts were wearing the complete sleep ensemble, their sleep was better than on other nights. This result might seem paradoxical since the sleep ensemble involved many electrodes and sensors. Our interpretation of this result relates to the effects of the experimental demands on the astronauts' behavior. The crewmembers who were not wearing the sleep ensemble would instrument those who were, and the non-instrumented crewmembers would try to get the others to sleep on time. On other nights, the crewmembers' adherence to their scheduled sleep-wake cycle was affected by other demands of the flight, whereas they may have seen it as their top priority to sleep at scheduled times during the nights they were fully instru-



mented. This interpretation was supported by an analysis of the actigraphically determined onset of the sleep episode on nights with and without sleep ensemble. The interval between scheduled bedtime and onset of the sleep episode was 42.1 (SE 14.1,  $n=5$ ) and 15.9 (9.2,  $n=5$ ) minutes for the non-monitored sleep and monitored sleep nights, respectively. Analyses of the time course of illuminance at the transitions of scheduled wake to sleep episodes provided further support for this interpretation. The lights on the middeck stayed on until as much as 30 to 40 minutes after scheduled bedtime.

### **Light Levels Varied Markedly, Perhaps Affecting Circadian Synchronization**

The light-dark cycles during these Space Shuttle missions may not have been optimal for circadian synchronization. In fact, if astronauts were to visit the flight deck during their presleep leisure time, they might be exposed to a short light pulse of 60,000 lux or so. Ground-based research has shown that short exposures to bright light can be surprisingly effective at resetting circadian phase. Such exposure to light in the evening would be maladaptive, because bright light exposure at this biological time of day results in a delay of circadian rhythms that are contraindicated for adaptation to a shorter-than-24-hour rest-activity cycle when phase advances are required.

### **Circadian Rhythm Changes in Space**

The results from the urinary cortisol measurements show that the circadian system was unable to keep pace with the advancing sleep-wake schedule on these missions. This is consistent with the results of recent ground-based simulations of human circadian adaptation to a 23.5-hour sleep-wake schedule in similar lighting conditions. Our data contrast with the findings of Dr. Monk and colleagues during the STS-78 mission on which the rest-activity schedules were very similar. This apparent discrepancy may be related to differences in methods of analysis or, alternatively, to the lower light levels on STS-90 compared to STS-78.

## **CONCLUSIONS AND PERSPECTIVE**

Our analyses highlight two specific aspects of the space environment that could contribute to the cumulative sleep loss seen in space: (1) the shorter-than-24-hour rest-activity cycles, and (2) the highly variable and, in some compartments of the spacecraft, very dim light-dark cycles.

Our data indicate that astronauts do not adapt fully to these schedules when exposed to these light-dark schedules. Recently, we investigated the ability of healthy volunteers to adapt to such non-24-hour rest-activity cycles in ground-based studies. The data demonstrated that in humans, the internal circadian oscillations are so robust that in the absence of adequate light-dark cycles, they will not synchronise to either a 23.5-hour rest-activity schedule (similar to Space Shuttle missions) or a 24.6-hour rest-activity schedule (the Martian day).

In this paper and in our full report, we have emphasized group data. Interindividual differences during spaceflight were, however, observed by us and by others (Gundel, 1997). Appreciation and investigation of such differences are warranted. For example, analysis of respiration during sleep in these astronauts revealed that sleep-disordered breathing was attenuated by spaceflight (see science report by Prisk et al. in this publication). For an understanding of sleep disturbances at the individual level, a comprehensive assessment of sleep physiology and circadian physiology may be required. Such integrative approaches may lead to some surprising interpretations of the changes in sleep duration observed during spaceflight (Dinges, 2001).

Circadian phase is a major determinant of sleep duration, structure, and performance; accurate assessment of circadian phase is a prerequisite for a reliable interpretation of sleep and performance data obtained during and after spaceflights. Implementation of noninvasive methods to assess circadian phase, for example on the basis of salivary melatonin, may be considered. The status of the sleep homeostat is another major determinant of performance. Acute sleep curtailment and cumulative sleep loss will affect the sleep homeostat and performance. New methodologies are being evaluated to assess on line the status of the sleep homeostat by electrophysiological and ocular parameters that would allow continuous monitoring of performance capability.

Circadian phase and sleep homeostasis interact in their determination of performance. Attempts to develop biomathematical models, in which these aspects of sleep and performance and the effects of light on the circadian system are integrated, have been published already. Future success and refinement of such predictive models will depend on continued collaboration between biomathematicians and physiologists as well as continued acquisition of more data on sleep, circadian rhythms, and light exposure of astronauts prior to, during, and after short- and long-duration space missions.

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